Electrical characterization of polymeric charge transport layers

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1.1 Introduction

The research on organic semiconductors started in the 1950s when small organic molecules in the crystalline state started to be investigated. Molecular crystals like naphthalene and anthracene were shown to exhibit semiconducting properties [1]. Already in the early 1960s, next to photoconductivity [2, 3], organic electroluminescent devices based on anthracene crystals were demonstrated by Pope et al. [4]. An important breakthrough came in 1977 when the first highly conducting organic polymer, chemically doped polyacetylene, was reported [5]. The initial excitement on this new class of materials decreased in the subsequent years because these doped conducting polymers were unstable in air, brittle, and difficult to process. However, in the middle of the 1980s the interest in undoped organic semiconductors, both polymers and small molecules, revived due to a number of important discoveries. First, at Eastman Kodak electroluminescent devices from thin film stacks of vacuum-sublimed small molecules were realized by Tang et al. [6]. Subsequently, field-effect transistors made from polythiophene [7] and from small conjugated oligomers [8] were reported. Then, in 1990 also electroluminescence from conjugated polymer-based diodes was discovered at Cambridge University [9]. In the middle of the 1990s also the first photovoltaic devices based on bulk-heterojunctions in blends of polymers or polymers and fullerenes were developed [10-13].

An advantage of conjugated polymers (CPs) is that by modification of their chemical structure they can be made soluble in common organic solvents. As a result polymer-based devices can be processed from solution [14] by spin coating, inkjet printing techniques or coating techniques like slot-die coating. This enables a low-cost high-speed production via roll-to-roll processing of electronic devices. As a result of this ease of processing conjugated polymers are promising to provide large-area, flexible, lightweight lighting systems, integrated circuits and solar cells.

Conjugated polymers are organic macromolecules which have a framework of alternating single and double carbon-carbon bonds. Single bonds are referred to as σ-bonds and are associated with a highly localized electron density in the plane of the molecule. Double bonds contain both a σ-bond and a π-bond, where the π-bond is the overlap between p_z orbitals of neighboring atoms along the conjugation path. The overlapping p_z orbitals establishe a delocalization of the electrons situated above and below the plane of the molecule. π-bands are either empty (called the Lowest Unoccupied Molecular Orbital - LUMO) or filled with electrons (called the Highest Occupied Molecular Orbital - HOMO). The band gap

of these materials determined from optical measurements is within the semiconductor range of 1–4 eV, which covers the whole range from infrared to ultraviolet region. A typical example of a conjugated polymer is polyacetylene, which consists only of a single chain of alternating single- and double-bonds (Figure 1-1).

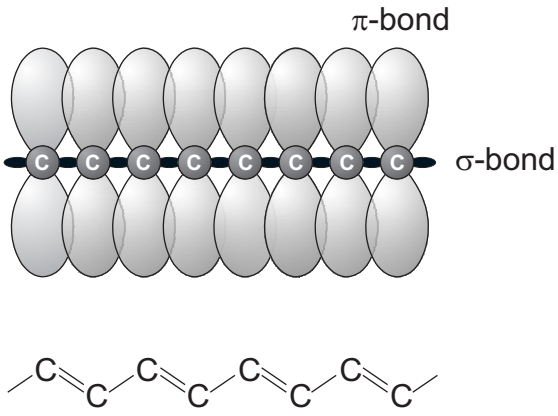

Figure 1-1. *Schematic representation of the electronic bonds between carbon atoms (above) in polyacetylene (below).*

The absence of an ideal 3D periodic lattice in polymer semiconductors complicates the description of charge transport processes in terms of standard semiconductor models. An ideal crystal has a three-dimensional architecture characterized by the infinite repetition of identical structure units in space. Its structure can be described in terms of a lattice characterized by long-range order and strongly coupled atoms [15]. For silicon or germanium this strong coupling results in the formation of long-range delocalized energy bands separated by a forbidden energy gap [15]. Charge carriers added to the semiconductor move in these energy bands with a relatively large mean free path. Carrier scattering significantly affects the carrier mobility, which depends on the effective mass of electrons and the temperature. Carrier mobility in the order of 10^{-1} m^2/Vs is reported for pure inorganic semiconducting crystals such as silicon or germanium. In organic crystals, such as pentacene, the atoms are held together by weak van der Waals or London forces. This weak coupling between molecules results in a narrow width for the valence and conduction bands and the band structure can be easily disrupted by introducing disorder in the system. Although organic molecular

crystals still exhibit band conduction, excitations and interactions localized on individual molecules play a predominant role. Their mobility, in the order of 10^{-3} m^2/Vs, is significantly lower than those of their inorganic counterparts. The Su-Schrieffer-Heeger (SSH) theory describes the electronic structure of conjugated polymers (CP) [16]. It takes account of electron-phonon coupling. Furthermore, a postulation is made in the model that the p_z orbitals may not be equally spreaded along the chain, but can be slightly paired. This p_z-pairing results in the common representation of the p_z electrons in alternating single and double bonds (conjugation, see figure 1-1). It also gives rise to the semiconducting behaviour of (undoped) CP's -they would have been metallic if the p_z orbitals would have been equally spreaded. These model calculations give rise to a whole spectrum of 'quasi-particles', both charged (net on-chain charge, e.g. by doping or charge injection) and uncharged. The most important uncharged particle is the soliton, which is a local distortion of the conjugation. It is essentially a local reversion of the conjugation, and is localized to several chain atoms. It can only exist in polyacetylene, because in this polymer each carbon atom in the chain is coupled to an identical carbon atom. Therefore, it makes no difference which two neighbors have their p_z orbitals paired. This is a so-called degenerate state. At the other hand, in for example poly(p-phenylen vinylene) (PPV), it matters which carbon atoms in the chain pair together, and a soliton cannot exist. The most important charged particle is the polaron. The polaron essentially is also a local distortion of the conjugation, but now initiated by an extra charge carrier (Figure 1-2) [17], considered to be delocalized (free) to a certain extent, as is illustrated in Figure 1-2. The polaron is the medium that in the models for CP's causes the charge transport.

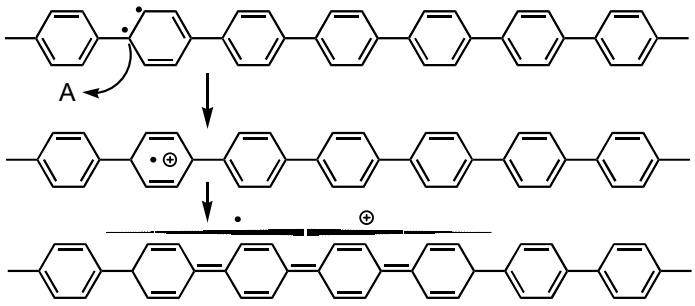

Figure 1-2. *Formation of a polaron in poly-(p-phenylene), shown for the case of doping with an electron acceptor. Picture taken from [19]*

A major problem when applying the SSH model to experimental systems is that most conjugated polymers do not have a well-ordered structural configuration

as crystals. The conjugation of the polymer backbone is easily disrupted by chemical or structural defects, such as chain kinks or twists. Experimentally, it has been found that the charge carrier mobility in these materials is in the range of 10^{-12} -10^{-10} m^2/Vs for polymer light-emitting diodes and 10^{-8} $-$ 10^{-5} m^2/Vs for polymer field-effect transistors. This is orders of magnitude lower than the mobility determined for organic crystals. Over the past decades intense research has been carried out in order to explain the transport of charge carriers in disordered polymer semiconductors which would justify such low mobility.

1.2 Charge transport in conjugated polymers

1.2.1 The role of disorder

A semiconducting polymer is not a perfect conjugated system, because its twisted and kinked chains and chemical defects cause conjugation breaks. Because of their spatial and energetically disordered configuration, these systems have no translation symmetry. The concept of band conduction by free charges does not apply. Instead, the formation of localized states is enhanced and a different theoretical approach is required. In order to participate to the transport, the charge carriers must hop between these localized states (inter- or intra-chain transitions). This usually leads to very low carrier mobility. To overcome the energy difference between two localized states, the carriers absorb or emit phonons. This process of phonon-induced hopping was suggested by Conwell [20] and Mott [21] in connection with metallic conduction in inorganic semiconductors. Miller and Abrahams proposed a hopping model based on a single-phonon jump rate description [22]. The hopping rate of carriers from occupied *i* to unoccupied j localized donor states depends on the height of the energetic barrier $E_j - E_i$ and the distance R_{ij} between the states *i* and *j*:

$$\nu_{i\to j} = \nu_0 \exp(-2\gamma a \frac{R_{ij}}{a}) \begin{cases} \exp\left[-\left(E_i - E_j\right)/k_B T\right] for E_i > E_j, \\ 1 for E_i < E_j \end{cases} \quad (1\text{-}1)$$

where the prefactor v_0 is the attempt-to-hop frequency, γ is the inverse localization length, a is the average lattice distance, and k_B is the Boltzmann constant. The first exponential term from Eq. 1-1 represents the tunneling probability and the second exponential term accounts for the temperature dependence of the phonon density.

Bässler [23] proposed in 1993 a charge transport model for disordered organic systems. He assumes that electron-phonon coupling is sufficiently weak so that the polaronic effects can be neglected, and the hopping rates can be described by the Miller-Abrahams formalism (Eq. 1-1). The charges hop in a regular array of hopping sites. In this way both positional disorder (fluctuation in inter-site distance) and energetic disorder (fluctuation in site-energy) are introduced. In this model, the energy distribution of localized states can be approximated by a Gaussian function [23]:

$$DOS_{Gauss} = \frac{N_t}{\left(2\pi\sigma_{DOS}\right)^2}\exp\left(-\frac{\varepsilon^2}{2\sigma_{DOS}{}^2}\right) \tag{1-2}$$

where N_t is the total density of sites, σ_{DOS} is the width of the Gaussian density of states (DOS) and the energy ε is measured relative to the center of the DOS. The choice for this particular DOS shape is supported by the fact that coupling between a charge carrier and a random distribution of static or induced dipoles leads to a Gaussian DOS function [24]. The charge transport in the Gaussian disorder model (GDM) cannot be solved analytically and therefore an alternative approach of Monte Carlo simulations has been applied [23]. Using the hopping rate from the Miller-Abrahams formalism, the Monte Carlo simulations revealed that carriers (in this case the electrons) with an arbitrary energy within a Gaussian DOS relax to an equilibrium level $-\sigma^2_{DOS}/k_BT$ below the center of the DOS distribution. The energy level that is relevant for the transport is located at $-(5/9)\sigma^2_{DOS}/k_BT$. This gives rise to the dependence $\mu\ (T) = \mu_0 \exp\ [-(2\sigma_{DOS}/3k_BT)^2]$. But the hopping mobility must depend also on the electric field since the average barrier height for energetic uphill jumps in field direction is reduced [23]. On the basis of the Monte Carlo simulations, the charge carrier mobility is temperature- and field-dependent, and in the limit of high electric fields is given by [23]:

$$\mu_{GDM} = \mu_\infty \exp\left[-\left(\frac{2\sigma}{3k_BT}\right)^2\right] \times \begin{cases} \exp\left[C\left(\left(\frac{\sigma}{k_BT}\right)^2 - \Sigma^2\right)\sqrt{E}\right] & for \Sigma \geq 1.5 \\ \exp\left[C\left(\left(\frac{\sigma}{k_BT}\right)^2 - 2.5\right)\sqrt{E}\right] & for \Sigma < 1.5 \end{cases} \tag{1-3}$$

where μ_0 is the mobility in the limit $T\rightarrow\infty$, with values between 10^{-6} and 10^{-5} m^2/Vs, C is a constant that depends on the site spacing, and Σ is the degree of positional disorder. A consequence of hopping in a Gaussian DOS is the non-Arrhenius behavior of the mobility [23].

Because the results of simulations performed within the frame of the standard Gaussian disorder model can explain the experimental results only at high fields (> 10^8 V/m), further improvement was necessary. A spatially correlated site-energy distribution was considered [25], which means that the energies are correlated over a greater length than the distance between hopping sites. Due to the correlation of energies of adjacent sites, the field dependence of the mobility extends to lower electric fields. Spatial correlations in site-energy may arise from long-range charge-dipole interactions in the material, where the disorder is determined by the random orientations of dipole moments of nearby molecules. In this correlated disordered model (CDM), the empirical expression for the mobility is given by [26, 27]:

$$\mu_{CDM} = \mu_\infty \exp\left[-\left(\frac{3\sigma}{5k_BT}\right)^2\right]\exp\left[C_0\left(\left(\frac{\sigma}{k_BT}\right)^{3/2}-\Gamma\right)\sqrt{\frac{eaE}{\sigma}}\right] \qquad (1\text{-}4)$$

where C_0=0.78, a is the intersite separation, and Γ= 2 for organic materials. The main difference between GDM and CDM is the predicted temperature-dependent field dependence. The GDM and CDM based hopping models of charge carriers in a Gaussian DOS have initially been used to explain the experimentally observed temperature- and field dependence of the hole mobility in light-emitting diodes based on poly(p-phenylene vinylene) (PPV) based derivatives.

1.2.2 Hole transport in conjugated polymers

Since the discovery of electroluminescence in poly(p-phenylene vinylene) (PPV) in 1990 [9] extensive research has been carried out to understand and develop polymer light-emitting diodes (LEDs). A typical single-layer polymer LED is presented in Figure 1-3. A thin polymer film is spin-coated from solution on a semitransparent bottom electrode, normally indium-tin-oxide (ITO), which forms the anode. A low work-function metal (calcium or barium) is evaporated on top of the polymer and serves as cathode.

The main processes that govern the operation of the polymer LED are: charge injection, charge transport and recombination (Figure 1-3b) [28]. Under forward bias, holes and electrons are injected from the anode and cathode, respectively. The charge carriers move through the polymer film and recombine. The energy released upon recombination is emitted as a photon through the semitransparent electrode. The emitted light can be tuned from red to blue, depending on the band gap of the polymer. In order to be injected from the electrodes, the charges must surmount or tunnel through a barrier at the polymer/electrode interface, which is determined by the position of the highest occupied molecular orbital (HOMO or π orbital) and the lowest unoccupied molecular orbital (LUMO or π* orbital) and the position of the electrode metal work-functions. A schematic band diagram of a PPV-based LED under forward bias using ITO as a hole injector and Ba as an electron injector is shown in Figure 1.3-b.

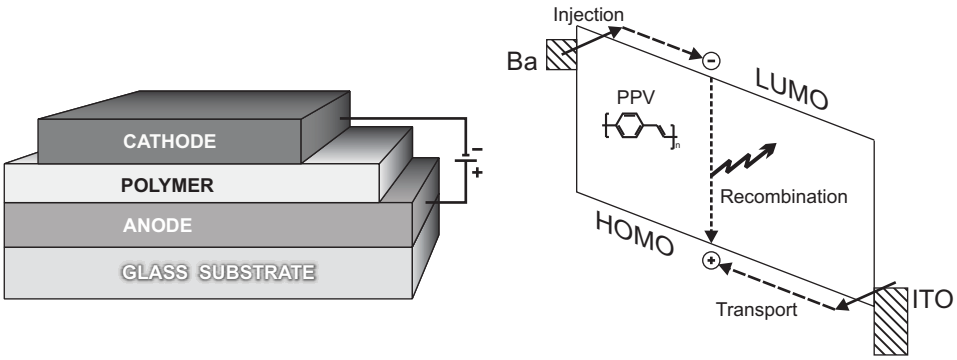

Figure 1-3. *Schematic representation of a polymer LED (a) and energy diagram of a PPV-based LED (b).*

In order to investigate the hole mobility in PLEDs, diodes with one hole injecting contact and one electron blocking contact, in this case Au, have been fabricated. Such a structure is called hole-only diode. As the active layer the solution processable PPV-derivative poly(2-methoxy-5-(3′,7′-dimethyloctyloxy)-p-phenylene vinylene) (OC_1C_{10}-PPV) is used. The experimentally measured current-voltage characteristics at low electric fields of these hole-only diodes show a quadratic behaviour [28], as shown in Figure 1-4, indicating that the current is

space-charge limited. In this case the current density is characterized by Child's law [29]:

$$J = \frac{9}{8}\varepsilon_0 \varepsilon_s \mu \frac{V^2}{L^3} \tag{1-5}$$

where ε_0 is the permittivity of vacuum, ε_s is the relative dielectric constant of the semiconductor, μ is the carrier mobility and L the thickness of the device. At low voltages the *J-V* characteristics are well described by the SCLC given by Eq. 1-5 (line), from which the zero-field mobility $\mu_p\ (0) = 5\times10^{-11}$ m^2/Vs is determined. At high biases the current starts to increase more rapidly with voltage and Eq. 1-5 is no longer valid. This suggests that the mobility increases with the applied voltage. By changing the temperature, it was also found that the mobility also depends on the temperature [30].

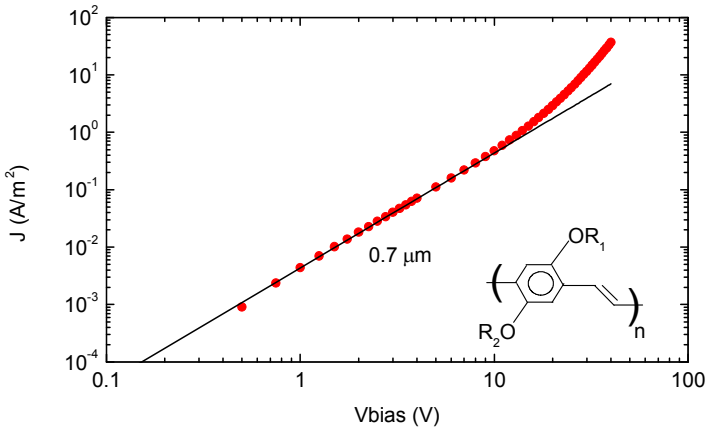

Figure 1-4. *J–V of OC_1C_{10}-PPV hole-only diode at room temperature. The polymer layer thickness is 700 nm. The solid line represents the prediction of the conventional SCLC model using Eq. 1-5.*

Initially, the hole transport in PPV has been described by the combination of the SCL conduction model with a temperature and field-dependent mobility [30]:

$$J = ep(x)\mu_p(F(x),T)F(x) \tag{1-6}$$

$$\frac{\varepsilon_0 \varepsilon_s}{e} \frac{dF(x)}{dx} = p(x) \tag{1-7}$$

$$\mu_p(F,T) = \mu(F=0) \exp\left[-\frac{\Delta}{k_B T} + \gamma\sqrt{F} \right] \tag{1-8}$$

where $p(x)$ is the density of holes at position x in the semiconductor film, $\mu(F = 0)$ is the zero-field mobility, Δ is the zero-field activation energy, and γ is the field dependence parameter. This empirical equation which gives the temperature and field dependence of the mobility (Eq. 1-8) was noticed for the first time in poly(N-vinyl carbazole) by Gill in 1972 [31].

1.2.3 Origin of the enhanced SCLC in PPV-based diodes

In a space charge-limited device an increase of the applied bias gives rise to a simultaneous increase of the electric field and charge carrier density. Consequently, at high voltages, it is difficult to distinguish between the contributions of the charge carrier density and the electric field to the mobility from the current-voltage characteristics. For the understanding of the charge transport in polymer devices it is crucial to know whether the current is governed by the field and/or the carrier density dependence of the mobility. In the first analysis of charge transport properties of polymer SCL devices [31] the charge carrier density dependence of the mobility had not been taken into account. Neglecting the density dependence of the mobility can lead to an incorrect charge carrier and field distribution in organic SCL diodes. In order to investigate the contribution of the charge carrier density to the mobility field-effect transistors have been used. The basic idea of a field-effect transistor is to modulate the current that flows between two ohmic contacts, the source and the drain electrodes, by applying a voltage to a third contact, the gate electrode. The gate electrode is electrically decoupled from the semiconductor by an insulating layer. By applying positive or negative gate voltages, induced charge carriers electrostatically accumulate or deplete in the semiconductor close to the semiconductor/insulator interface giving rise to band bending in the semiconductor. In this way the field-effect current is varied in the source-drain channel. In contrast with conventional monocrystalline silicon, the transport properties of disordered organic

semiconductors are dominated by localized states. By applying a gate voltage in a field-effect transistor, the charge carriers accumulate in the organic semiconductor close to the insulator, thereby filling the lower localized states. Any additional charges in the system will occupy states at relatively high energies, which means that they will need less activation energy to jump to other sites. As a result the mobility will be enhanced and is expected to increase with charge carrier density [32,33].

In order to explain the charge transport in polymer FETs a model based on variable range hopping was developed by Vissenberg and Matters [32]. The variable range hopping model suggests that charge carriers may either hop over a small distance with a high activation energy or hop over a long distance with a low activation energy. This transport model takes into account the filling of localized states with charge carriers in contrast to the one developed by Bässler, which is a one particle model [23]. The model predicts that at low carrier densities and low temperatures, the transport properties are determined by the tail states of Gaussian DOS, which is approximated by an exponential DOS [32]:

$$DOS_{\exp on} = \frac{N_t}{k_B T} \exp\left(\frac{\varepsilon}{k_B T_0} \right) \tag{1-9}$$

where N_t is the number of states per volume unit, T_0 is the width of the exponential DOS, and ϵ the level energy. It is considered that the energy distribution of the carriers at equilibrium is given by the Fermi-Dirac distribution. Using percolation theory [34], an expression for the conductivity can be derived as a function of the occupation fraction δ and the temperature T [32]:

$$\sigma(\delta, T) = \sigma_0 \left(\frac{\delta N_t (T_0 / T)^4 \sin\left(\pi \frac{T}{T_0} \right)}{(2\alpha)^3 B_c} \right)^{T_0 / T} \tag{1-10}$$

where σ_0 is a prefactor for the conductivity, and B_c is the critical number for the onset of percolation. For three-dimensional amorphous systems B_c=1.8 [35]. The conductivity expressed by Eq. 1-10 has an Arrhenius-like temperature dependence $\sigma \sim \exp[-E_a/k_B T]$ explained by the fact that in an exponential DOS the hopping can be described in terms of activation from the Fermi level to a specific transport level [36]. Moreover, the conductivity increases superlinearly with the charge carrier

density $\sigma \sim \delta^{T_0/T}$. This is due to the fact that by increasing the carrier density the states are filled and an activated jump to the transport energy is facilitated.

From electrical measurements using as active material OC_1C_{10}-PPV in a FET geometry a field-effect mobility of 4.7×10^{-8} m^2/Vs at $V_g = -19$ V at room temperature has been obtained [37] . Surprisingly, this value for the field-effect mobility is approximately three orders of magnitude larger than the mobility value determined from a hole-only diode, as shown in Figure 1-4. The question is why the experimental mobilities for the same polymer differ when measured in different device geometries (LED and FET). The answer is related to the charge carrier density regime in which the two devices operate. For a 700 nm film of OC1C10-PPV for the voltage range applied of 1 V to 10 V (Figure 1-4) the mobility is charge carrier and field-independent. This voltage range corresponds to hole density of 2.5×10^{20} to 2.5×10^{21} m^{-3}. [37] In FETs, the charge carrier density is much larger at the semiconductor/insulator interface, ranging from $\sim 10^{23}$ m^{-3} at low gate voltage (-1 V) to 3×10^{25} m^{-3} at a gate bias of -20 V. The experimental mobilities obtained from the hole-only diode and the field-effect transistors are presented together in Figure 1-5 for OC_1C_{10}-PPV. The combined results from the diode and field-effect measurements show that the hole mobility is constant for charge carrier densities < 10^{22} m^{-3} and increases with a power law for densities > 10^{22} m^{-3}. The big differences in mobility values obtained from diodes and FETs, based on a single semiconducting disordered polymer, are due to the large differences in charge densities.

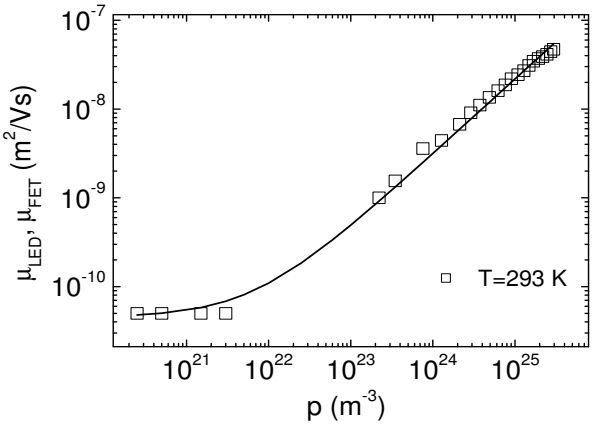

Figure 1-5. *Hole mobility as function of hole density p in hole-only diode and FET for OC_1C_{10}-PPV (symbols) [37]. The dashed lines is a guide for the eye.*

Combination of the diode and field-effect measurements shows that at room temperature the dependence of the hole mobility on charge carrier density can be described by the empirical relation [37]:

$$\mu_h(p,T) = \mu_h(0,T) + \frac{\sigma_0}{e}\left(\frac{\left(\frac{T_0}{T}\right)^4 \sin\left(\pi\frac{T}{T_0}\right)}{(2\alpha)^3 B_c}\right)^{T_0/T} p^{T_0/T-1}, \qquad (1\text{-}11)$$

where $\mu_h(0,T)$ is the hole mobility at low densities obtained from the quadratic SCL current. It should be noted that this unification is only possible for highly disordered polymers such as OC_1C_{10}-PPV, in which the charge transport is isotropic [37].

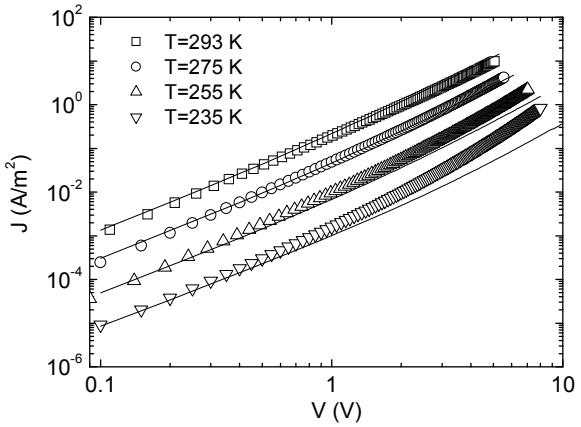

Figure 1-6. *Temperature dependent J–V characteristics of the OC_1C_{10}-PPV hole-only diode. The solid lines represent the prediction from Eq. 1-11.*

Now knowing how the mobility depends on density the SCL current was calculated using only the density-dependent mobility as given by Eq. 1-11 [38]. By numerically solving Eqs. 1-6, 1-7 and 1-11, the *J-V* characteristics of OC_1C_{10}-PPV hole-only diodes are obtained, as shown in Figure 1-6 by the solid lines.

It can be observed that at T = 275 K and T = 293 K the calculated SCL current density for OC_1C_{10}-PPV at high fields is in good agreement with the

experimental current densities. Furthermore, from Figure 1-6 it appears that at temperatures lower than $T = 275$ K the carrier density dependence of the mobility alone does not explain the observed increase of the SCLC. At low temperatures the field dependence becomes more important. This is due to the fact that at low temperatures the activated hops between neighboring sites are strongly suppressed, which means that the charge transport is also suppressed. Application of an electric field leads to a reduction of these dominant barriers for the charge transport in the field direction, resulting in strong field dependence. Pasveer *et al* [39] have presented the Extended Gaussian Disorder Model (EGDM) of the mobility that is both field- and charge carrier concentration dependent. According to this model, that has also been experimentally verified, the carrier concentration dependence is dominating at room temperature when the field is not very high. At low temperature or at high field the electric field dependence becomes important. The Pasveer mobility is given by:

$$\mu(T,p,E) = \mu_p(T,p)\mu_E(T,E) \tag{1-12a}$$

where

$$\mu_p(T,p) = \mu_0 \exp\left(-0.42\left(\frac{\sigma}{k_B T}\right)^2 + \frac{1}{2}\left(\left(\frac{\sigma}{k_B T}\right)^2 - \frac{\sigma}{k_B T}\right)\left(2pa^3\right)^{\delta}\right) \tag{1-12b}$$

and

$$\mu_E(T,E) = \exp\left(0.44\left(\left(\frac{\sigma}{k_B T}\right)^{3/2} - 2.2\right)\sqrt{1 + 0.8\left(\frac{Eea}{\sigma}\right)^2 - 1}\right) \tag{1-12c}$$

The exponent δ in (3.10b) is given by

$$\delta = 2\frac{\ln\left(\left(\sigma k_B T\right)^2 - \sigma / k_B T\right) - \ln\left(\ln 4\right)}{\left(\sigma / k_B T\right)^2} \tag{1-12d}$$

At low carrier concentrations the average energy of the charge carriers is given by the equilibrium energy $-\sigma^2/kT$. The charge carriers only occupy the tail states of the Gaussian DOS and the average distance between charge carriers is sufficiently large that the transport of a carrier is not affected by the presence of other carriers. As a result the mobility is constant at low densities. Above a certain critical concentration the Fermi-level will pass the equilibrium level and the

average energy of the charges will increase substantially with increasing concentration [40]. As a result the energy required to hop to neighboring sites will decrease, leading to a mobility that increases with charge carrier density. Note that the carrier concentration becomes more important as the disorder in the material is increased. The domination of the density dependence at room temperature has also been verified by studying the thickness dependence of PPV-based SCL hole-only devices [41]. The EGDM model has recently been extended by also taking into account spatial correlations between the site energies. In recent studies, however, in two commonly used classes of conjugated polymers no indications for correlation effects were found [42, 43]. It should be noted that in these charge transport models the formation of polarons as sketched in figure 1-3 is neglected. When polaronic effects are dominating the localization of charge carriers instead of disorder hopping rates following Marcus theory [44] would be more appropriate. However, in that case an increase of the mobility with charge carrier density is highly unlikely [45].

1.3 Summary

Since the discovery of electroluminescence in conjugated polymers it has been recognized that charge transport is a key ingredient for the efficiency of the polymer light-emitting diodes (PLEDs). From temperature dependent current-density vs. voltage characteristics it has been obtained that the hole transport in poly(dialkoxy-p-phenylene vinylene) (PPV) is governed by the dependence of the hole mobility on electric field and charge carrier density. At room temperature the charge carrier density dependence of the mobility is dominant, while at low temperatures the field dependence of the mobility must be taken into account. The origin of the hole mobility is generic for a large class of disordered materials, and arises from hopping in a system with both energetic and structural disorder. In the next chapter an overview of the device operation of polymer based LEDs is given.

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